【Grant-in-Aid for Scientific Research (S)】

Demonstration of High-Efficiency Relativistic High-Order Harmonic Generation Using Ultra-High-Intensity Mid-Infrared Lasers

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Purpose and Background of the Research

●Outline of the Research

If high-brightness X-ray pulses, which have so far only been generated at large-scale X-ray free-electron laser (XFEL) facilities, could be produced using compact, laboratory-scale equipment, it would bring innovations to a wide range of fields. Based on the idea that this could be realized in the future through the relativistic interaction between ultra-high-intensity mid-infrared laser pulses and solid-surface plasmas—a concept proposed and explored in this study—we are advancing new research by further developing our ultrashort-pulse mid-infrared laser technology. As an intermediate step, this study aims to demonstrate a novel method for generating high-intensity, coherent, ultrashort ultraviolet pulses with peak powers exceeding one gigawatt (GW) using a tabletop device.

Figure 1. Concept of the Compact High-Intensity Coherent X-ray Generation Device

●Previous Challenges

High-intensity ultraviolet to X-ray sources have significant societal impact. Key advancements include: (1) soft X-ray lasers using amplified plasmas (1980s–90s), (2) gas-based high-order harmonic generation (1990s–2000s), and (3) X-ray free-electron lasers (XFELs) since 2010. While HHG struggles to balance efficiency and shorter wavelengths, XFELs, though powerful, remain limited to fundamental research due to their large size. Miniaturizing such sources for industrial and medical use requires entirely new technology.

●Relativistic High-Order Harmonic Generation

When an ultra-high-intensity near-infrared (NIR) laser ($\geq 10^{18}$ W/cm^2, 800 nm) hits a solid, an overcritical-density plasma forms instantly. Electrons in this plasma, accelerated to relativistic speeds by the laser field, generate high-order harmonics in the ultraviolet to soft X-ray range—a process known as RHHG (Figure 2). Unlike gas-based HHG, RHHG uses dense plasmas, allowing higher laser intensities and enabling shorter-wavelength harmonics as intensity increases.

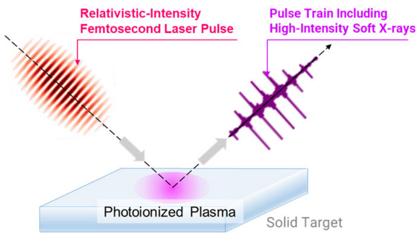

Figure 2. Schematic of RHHG.

●Our Concept

This study proposes a mid-infrared laser-driven coherent soft X-ray source as a solution to existing challenges. By leveraging the large electromagnetic potential of long-wavelength, ultra-high-intensity lasers, we explore a novel X-ray generation method centered on mid-infrared (MIR) lasers. While ultra-high-intensity MIR lasers remain undeveloped, achieving efficient high-order harmonic generation (HHG) could open new directions in optical and plasma sciences. Current RHHG requires high-intensity near-infrared (NIR) lasers, demanding large-scale facilities. If a high-efficiency RHHG method using a medium-power laser (<10 TW) can be developed, compact high-intensity coherent soft X-ray sources become feasible. Our approach uses a 4-μm MIR ultra-high-intensity laser, reducing the required laser intensity to 1/25 of conventional systems, enabling efficient RHHG with a simpler setup. This study aims to develop the world's first terawatt-class MIR laser and demonstrate high-efficiency RHHG.

Expected Research Achievements

●Research Plan Overview

During the research period, we aim to: (1) Demonstrate solid-state laser technology for generating mid-infrared femtosecond laser pulses with peak power exceeding 1 TW. (2) Demonstrate RHHG technology for generating EUV sub-femtosecond laser pulses with peak power exceeding 1 GW. The mid-infrared femtosecond laser developed in this study will consist of an optical parametric amplifier and an Fe:ZnSe chirped pulse amplifier, producing ultra-high-intensity laser pulses at 4 μm. This system will achieve a focused intensity of 1×10^{18} W/cm^2, enabling unexplored RHHG experiments. Although generating hard X-rays like XFELs is challenging, the ultra-short pulses in the attosecond regime could reach 1 GW within this study and potentially 1 TW in the future, surpassing XFELs. This research will provide a clear outlook on the future of RHHG studies.

●Mid-Infrared Laser Development

We aim to develop the world's first terawatt-class femtosecond laser in the 4-μm mid-infrared region. Figure 3 illustrates the schematic of the laser system under development. We have already built a system combining an optical parametric amplifier and an Fe:ZnSe chirped pulse amplifier, achieving a peak power exceeding 1 GW. To further increase output, we will develop a second-stage amplifier. The current world record for Fe:ZnSe laser peak output is ~20 GW, but by integrating our expertise in mid-infrared lasers, high-energy pulse lasers, and ultrashort pulse technologies, we aim to be the first to achieve over 1 TW peak power.

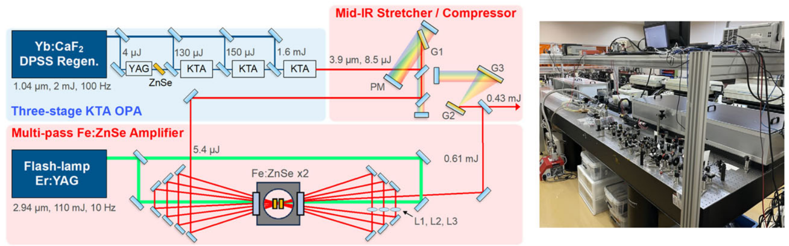

Figure 3. Mid-Infrared Femtosecond Laser System Under Development

Homepage Address, etc.	https://en.laser.kuicr.kyoto-u.ac.jp/ (Laser-Matter Interaction Science Division, Institute for Chemical Research, Kyoto University)